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Dynamic Reference-based Voltage Droop Control for VSC-MTDC System

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Abstract – The use of voltage source converter multi-terminal direct current (VSC-MTDC) systems is anticipated to increase from the introduction of wind farms and super grids in the near future. Effective control of the DC voltage in VSC-MTDC systems is an important research topic. This paper proposes a new dynamic reference-based voltage droop control to control the DC voltage in VSC-MTDC systems more effectively. The main merit of the dynamic reference-based voltage droop control is that it can reduce the steady-state error in conventional voltage droop control by changing references according to the system operating conditions. The performance of the proposed control was tested in a hardware-in-the-loop simulation (HILS) system based on the OPAL-RT real-time digital simulator and four digital signal processing boards.

Keywords: Multi-terminal VSC-MTDC, Hardware-in-the-loop simulation (HILS), HILS system based on OPAL-RT RTDS, Dynamic reference-based voltage droop control

1. Introduction

The fast growth of wind farms and super grids has led to rising interest in multi-terminal direct current (MTDC) systems. Recent advances in modular multi-level converters (MMCs) have led to increased research on voltage source converter MTDC (VSC-MTDC) applications [1-3]. In particular, DC voltage control schemes such as voltage margin control and voltage droop control are being developed to realize stable and effective control for the DC voltage of an MTDC system [4-7].

In voltage margin control, a converter controls the DC voltage of a VSC-MTDC in the normal state as a regulator. When the DC voltage rises or drops from mismatches between the power supply and power demand, other converters supply or receive power according to DC voltage references to maintain the DC voltage within the operating range. However, one drawback is the slow dynamic response of the control scheme [8-12].

In voltage droop control, all converters have the same control role of controlling the DC voltage by the droop function. Thus, this control has a simpler structure than voltage margin control. However, its drawback is the steady-state error that occurs in general droop control applications [13-17].

This paper proposes a new dynamic reference-based voltage droop control that improves upon the conventional voltage droop control by reducing the steady-state error while maintaining a simple structure. In Section 3, the principle of the control is described in detail. To demonstrate the performance of the control in the laboratory, a hardware-in-the-loop simulation (HILS) system was developed. The HILS system was composed of four digital signal processing (DSP) boards for implementing the proposed control in the four converters of a four-terminal VSC-MTDC system as an embedded system and the OPAL-RT real-time digital simulator (RTDS) for real-time modeling and simulation of the rest of the four-terminal VSC-MTDC system. The performance of the proposed control was compared with the performances of voltage margin control and voltage droop control in the HILS system.

2. Conventional Control Schemes

2.1 Voltage margin control

Eq. (1) expresses the voltage margin in voltage margin control for stable control of the DC voltage of a VSC-MTDC system. When the DC voltage of the VSC-MTDC system is maintained within the voltage margin, the controller of a converter controls the DC voltage as a voltage regulator, and the controllers of other converters keep the real power constant based on references. Eq. (2) expresses the current reference determined according to the system voltage, and Fig. 1 shows the voltage margin controller based on Eq. (2) [18, 19].

$$V_{margin} = V_{dc,ref}^{high} - V_{dc,ref}^{low} \quad (1)$$

where V_{margin} is the voltage margin, $V_{dc,ref}^{high}$ is the upper

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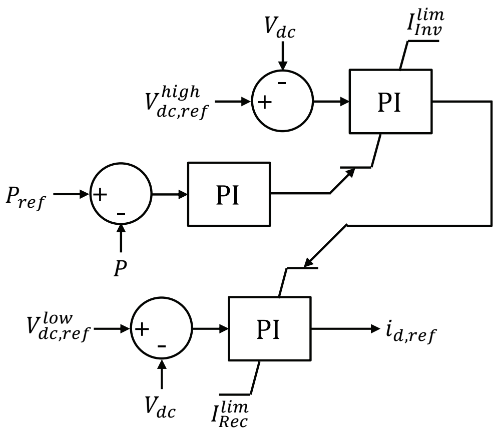

Fig. 1. Block diagram of voltage margin control.

limit of the DC voltage reference, and $V_{dc,ref}^{low}$ is the lower limit of the DC voltage reference.

$$i_{d,ref} = \begin{cases} (V_{dc,ref}^{high} - V_{dc})\left[k_P + \frac{k_I}{s}\right] \mathit{If}\ V_{dc} \geq V_{dc,ref}^{high} \\ \left(V_{dc,ref}^{low} - V_{dc}\right)\left[k_P + \frac{k_I}{s}\right] \mathit{If}\ V_{dc} \leq V_{dc,ref}^{low} \\ \left(P_{ref} - P\right)\left[k_P + \frac{k_I}{s}\right] \mathit{If}\ V_{dc,ref}^{low} < V_{dc} < V_{dc,ref}^{high} \end{cases} \tag{2}$$

where P_{ref} is the reference of the real power, and $i_{d,ref}$ is the reference of the converter current on the d-axis.

The voltage margin control has a slow dynamic response because of its control structure; as a drawback, a relatively large voltage margin is needed to avoid interactions between converters [18, 19].

2.2 Voltage droop control

In voltage droop control, stable control of the DC voltage is realized by determining the real power output of converters in the VSC-MTDC according to the change in voltage. The droop gain is defined by the relation between the real power output of converters and the DC voltage limits as determined by the VSC-MTDC condition given in Eq. (3):

$$\rho = \frac{V_{dc}^{max} - V_{dc}^{min}}{P_{Rec}^{lim} - P_{Inv}^{lim}} \tag{3}$$

where ρ is the droop gain, V_{dc}^{max} is the maximal value of the DC voltage, V_{dc}^{min} is the minimal value of the DC voltage, P_{Rec}^{lim} is the limit of a converter working as a rectifier, and P_{Inv}^{lim} is the limit of a converter working as a inverter.

Fig. 2 shows a block diagram of voltage droop control based on Eqs. (4) and (5) [20, 21].

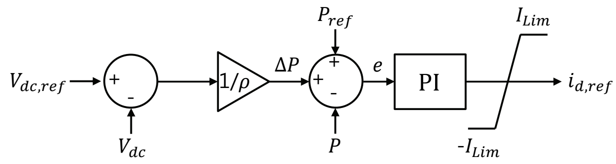

Fig. 2. Block diagram of voltage droop control.

$$e = P_{ref} - P + \frac{(V_{dc,ref} - V_{dc})}{\rho} = 0 \tag{4}$$

$$V_{dc} = V_{dc,ref} + \rho\left(P_{ref} - P\right) \tag{5}$$

where $V_{dc,ref}$ is the reference DC voltage.

In voltage droop control, the advantage is that the DC voltage can be controlled by multiple converters without a communication link. However, the drawback of voltage droop control is the steady-state error.

3. Proposed Dynamic Reference-based Voltage Droop Control

This paper proposes a new DC voltage droop controller based on dynamic references that reduces the steady-state error of conventional voltage droop control by changing the references for the voltage droop control according to the VSC-MTDC condition. It is called dynamic reference-based voltage droop control. The principle of the proposed control is shown in Figs. 3 and 4. When the DC voltage is

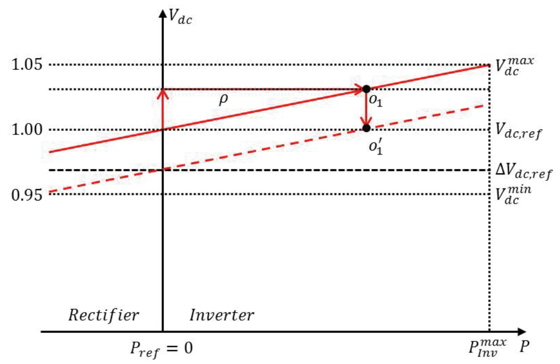

Fig. 3. P-V_{dc} curve when voltage is increasing.

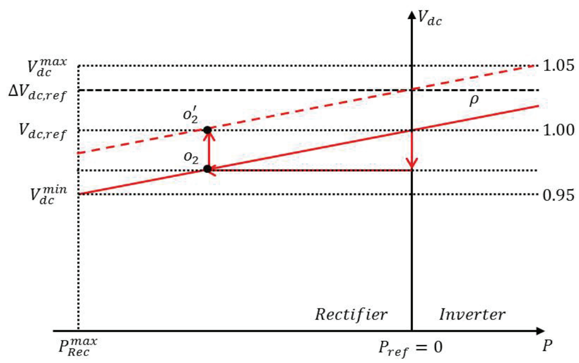

Fig. 4. P-V_{dc} curve when voltage is decreasing.

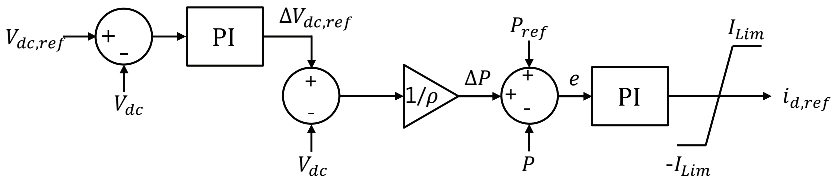

Fig. 5. Block diagram of dynamic reference-based voltage droop control.

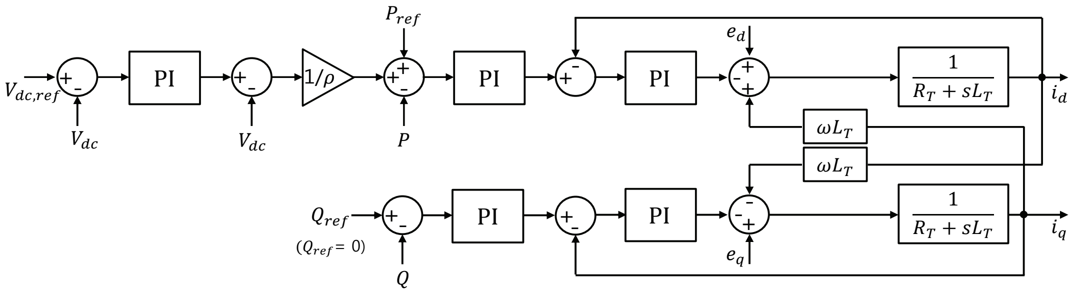

Fig. 6. Block diagram of control system of VSC-HVDC with current control.

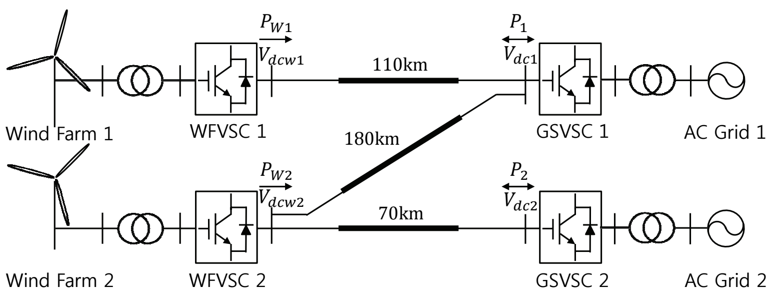

Fig. 7. Layout of four-terminal VSC-MTDC system with wind farms and AC grids.

increasing, it reaches point O_1 shown in Fig. 4 and produces a steady-state error. To reduce this error, the proposed control intentionally changes the reference of the DC voltage to point O_1'. When the DC voltage is decreasing, it reaches point O_2 shown in Fig. 5 and produces a steady-state error. To reduce this error, the proposed control intentionally changes the reference of the DC voltage to point O_2'.

Fig. 5 shows a block diagram of the dynamic reference-based voltage droop control. Fig. 6 shows a block diagram of the control system of a VSC-HVDC with current control. The dynamic reference to reduce the steady-state error of the voltage droop control can be obtained by Eqs. (6) and (7).

$$\Delta V_{dc,ref} = (V_{dc,ref} - V_{dc})\left[k_P + \frac{k_I}{s}\right] \quad (6)$$

$$\Delta P = \frac{\Delta V_{dc,ref} - V_{dc}}{\rho} \quad (7)$$

where V_{dc} is the DC voltage and $\Delta V_{dc,ref}$ is the dynamic reference.

4. Hardware-in-the Loop Simulation System for Testing Performance of DC Voltage Controller

Fig. 7 shows the test four-terminal VSC-MTDC system with wind farms and AC grids, which was used to test the performance of the proposed dynamic reference-based voltage droop control. Table 1 lists the parameters of the system [22, 23].

Fig. 8 shows the configuration of the developed HILS system. The 4-terminal VSC-MTDC system was modeled in the OPAL-RT RTDS. The conventional control schemes and the proposed control scheme were implemented in 4 DSP boards. The DSP boards receives measured voltage and current information from the OPAL-RT RTDS and

Table 1. Parameters of four-terminal VSC-MTDC system.

AC Grid	3500MVA	VSC Freq.	2.5kHz
AC Voltage	220/180kV	DC Capacitor	75 μ F
WFVSC 1	400MVA	DC Voltage	400kV
WFVSC 2	400MVA	Cable R/km	0.015 Ω
GSVSC 1	500MVA	Cable L/km	0.792mH
GSVSC 2	400MVA	Cable C/km	14.4nF

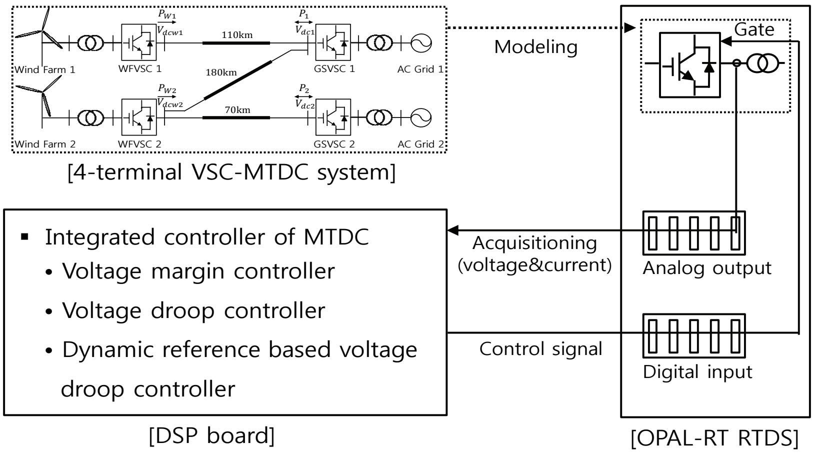

Fig. 8. Configuration of HILS system.

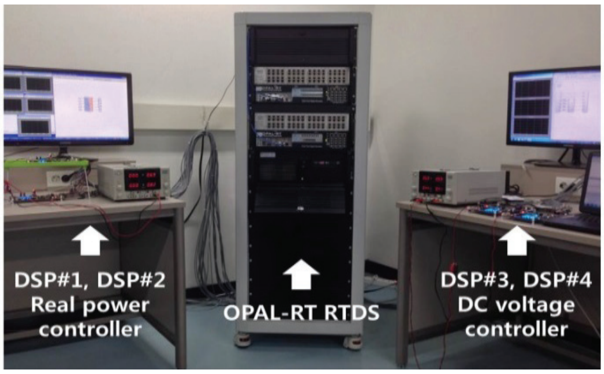

Fig. 9. HILS system developed in the laboratory.

sends PWM signals to IGBT gates of four VSCs in the OPAL-RT RTDS by real-time.

Fig. 9 shows the developed HILS system, which was based on four DSP boards as controllers of four VSCs and OPAL-RT RTDS as a real-time digital simulator to test the performance of the proposed control. In the HILS system, DSP boards 1 and 2 control the real power of WFVSC 1 and WFVSC 2, and DSP boards 3 and 4 control the DC voltage using GSVSC 1 and GSVSC 2. The rest of the four-terminal VSC-MTDC system was modeled with the real-time simulation software RT-LAB. The four DSP boards and OPAL-RT RTDS exchange digital and analog data by real-time communication. Voltage margin control and conventional voltage droop control were implemented with the four DSP boards to compare the control performances of the different schemes.

5. Test Results

In order to evaluate the performance of the dynamic reference-based voltage droop control in the HILS system, two operation conditions (Cases 1 and 2) were applied to the four-terminal VSC-MTDC system shown in Fig. 7. Permanent three-phase ground faults were applied near the wind farm 1 side at 0.5 s (Case 1) and near the AC side of GSVSC 1 (Case 2). For the initial conditions of the two cases, WFVSC 1 transferred a real power of 0.2 pu, and WFVSC 2 transferred a real power of 0.4 pu, GSVSC 1 and GSVSC 2 were used for the proposed control scheme.

5.1 Case 1

Fig. 10 shows the real power transferred from each converter by the dynamic reference-based voltage droop controller when the fault occurred near the wind farm 1 side at 0.5 s. P_1 and P_2 represent the real power outputs of GSVSC 1 and GSVSC 2, respectively, and P_{W1} and P_{W2} represent the real power outputs of WFVSC 1 and WFVSC 2, respectively. P_1 and P_2 were changed simultaneously by the droop gain. However, P_{W1} dropped to zero because of the permanent fault at 0.5 s. GSVSC 1 and GSVSC 2 decreased P_{W1} and P_{W2} to compensate for P_{W1}, which was decreased to zero from WFVSC 1. Fig. 11 shows that the DC voltages in the four converters were stably controlled during the fault. The results show that the Vdc1 and Vdc2 of two converters, GSVSC 1 and GSVSC 2, controlled by the proposed control scheme were controlled well without a steady-state error as designed.

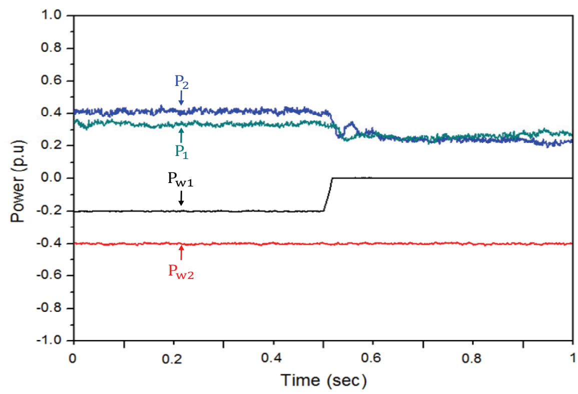

Fig. 10. Real power transferred from converters (Case 1).

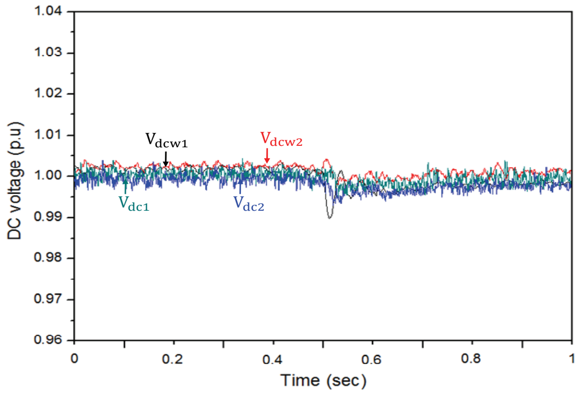

Fig. 11. DC voltages (Case 1).

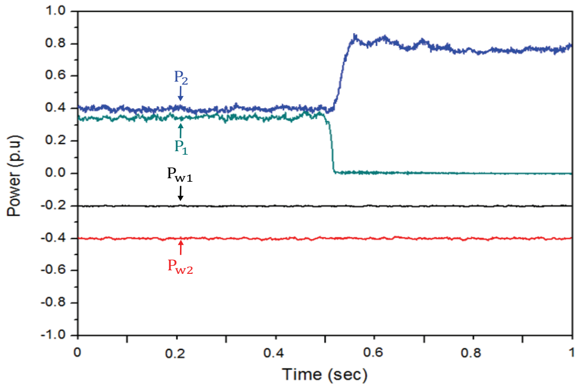

Fig. 12. Real power transferred from converters (Case 2).

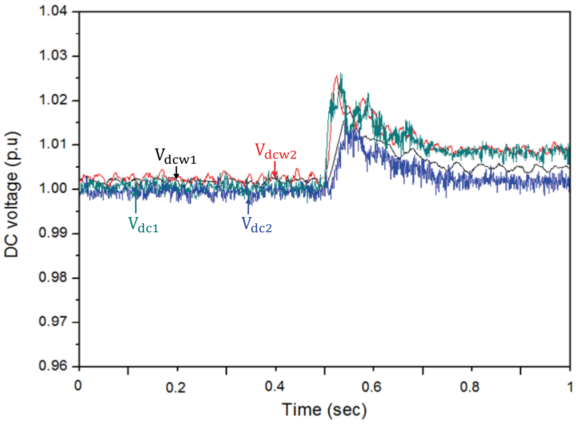

Fig. 13. DC voltages (Case 2).

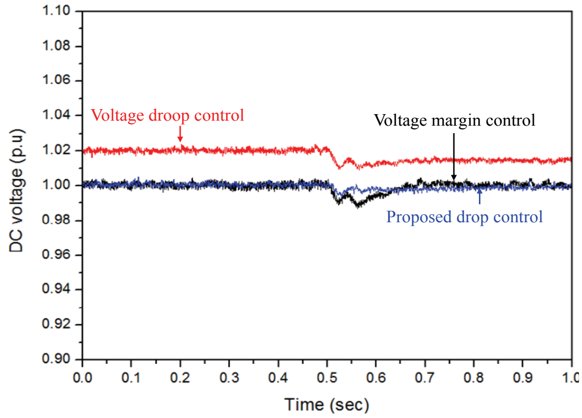

Fig. 14. Performance comparison (Case 1).

5.2 Case 2

Fig. 12 shows the real power transferred from each converter by the dynamic reference-based voltage droop controller when a fault occurred near the AC side of GSVSC 1 at 0.5 s. P_{W1} and P_{W2} were continuously maintained during the fault. Because the P_1 transferred from GSVSC 1 was dropped to zero by the fault, GSVSC 2 increased P_2 to compensate for the real power shortage to control the DC voltage. Fig. 13 shows that the DC voltage was controlled stably during the fault. The results show that the Vdc2 of GSVSC 2 controlled by the proposed control scheme was controlled well without a steady-state error as designed. However, Vdc1 was not controlled because the AC fault was applying to the AC side of GSVSC 1 was applied.

5.3 Performance comparison of controllers

Fig. 14 shows the DC voltages with each control when the fault occurred near the wind farm 1 side at 0.5 s (Case 1) to compare control performances. The results show that the voltage droop control controlled the DC voltage to 1.01 pu, which implies a steady-state error of 0.01 pu. However, the voltage margin control and proposed dynamic reference-based voltage droop control controlled the DC voltages to 1.0 pu, so there was no steady-state error.

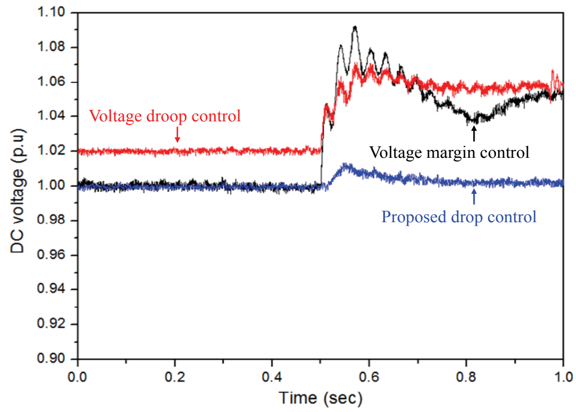

Fig. 15. Performance comparison (Case 2).

Fig. 15 shows the DC voltages with each control when the fault occurred near the AC side of GSVSC 1 at 0.5 s (Case 2) to compare control performances. The DC voltages with the voltage margin control and voltage droop control were controlled to 1.045 pu and 1.038 pu, respectively. These results show that both controls produced a steady-state error. However, the DC voltage with the proposed dynamic reference-based voltage droop control was

Table 2. Performance comparison of controls.

Controller	Case 1	Case 2
Voltage margin	1.0 pu	1.045 pu
Voltage droop	1.016→1.01 pu	1.016→1.038 pu
Dynamic reference based voltage droop	1.0 pu	1.0 pu
Controller	Case 1	Case 2

controlled to almost 1.0 pu. This means that the proposed control can reduce the steady-state error relatively well.

Table 2 summarizes the performance test results. The proposed control provided the best performance because it produced new control references to reduce the steady-state errors depending on the operating conditions.

6. Conclusion

This paper proposed a new dynamic reference-based voltage droop controller to control the DC voltage in a VSC-MTDC system. The performance of the controller was tested using a developed HILS system and compared against voltage margin control and voltage droop control. In the results, the proposed controller showed the best performance because it can produce control references dynamically to reduce the steady-state error.

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